International Journal of Surgery 7 (2009) 431–440

Contents lists available at ScienceDirect

International Journal of Surgery

journal homepage: www.theijs.com

Review

Current status of robotic assisted pelvic surgery and future developments

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ARTICLE INFO

Article history:
Received 31 July 2009
Accepted 19 August 2009
Available online 6 September 2009

Keywords:
Robots
Minimally invasive surgery
Telepresence surgery
Pelvic surgery

ABSTRACT

Aims: The aim of this review is to assess the role of robotics in pelvic surgery in terms of outcomes. We have also highlighted the issues related to training and future development of robotic systems.
Materials and methods: We searched MEDLINE, EMBASE and the Cochrane Databases from 1980 to 2009 for systematic reviews of randomised controlled trials, prospective observational studies, retrospective studies and case reports assessing robotic surgery.
Results: During the last decade, there has been a tremendous rise in the use of robotic surgical systems for all forms of precision operations including pelvic surgery. The short-term results of robotic pelvic surgery in the fields of urology, colorectal surgery and gynaecology have been shown to be comparable to the laparoscopic and open surgery. Robotic surgery offers an opportunity where many of these obstacles encountered during open and laparoscopic surgery can be overcome.
Conclusions: Robotic surgery is a continually advancing technology, which has opened new horizons for performing pelvic surgery with precision and accuracy. Although its use is rapidly expanding in all surgical disciplines, particularly in pelvic surgery, further comparative studies are needed to provide robust guidance about the most appropriate application of this technology within the surgical armamentarium.

1. Introduction

Minimally invasive surgery has expanded rapidly since the first laparoscopic cholecystectomy.[1] This was driven by the quest for smaller incisions, faster recovery, less stay related complications and improved dexterity, which gained further momentum as a result of the introduction of robotics to surgery. The era of robotic surgery dawned in early 1990s,[2] and many of the current systems emerged by the end of that decade. These include the 'master-slave robotic systems' such as the da Vinci and ZEUS surgical systems, which allowed entry to an era where poor visibility, hand tremors, limited freedom of movement and bulky instruments were not a problem.[3]

The da Vinci system, described as the "tele-presence surgery" was developed by NASA and the US defence department with the aim to allow surgeons to operate on wounded soldiers from a remote location. This system permitted real-time video image contact between the patient and surgeon. The da Vinci is not a fully automated robot in the true sense but is in fact a "master-slave" system that allows the surgeon to control the function of the robot. It consists of a cart with robotic arms delivering a variety of articulating instruments including cameras. At the console is a pair of binoculars, which displays 3D video image of the operating field. As the surgeon views the surgical field through these binoculars, he descends into the virtual 3D operative field and perceives himself to be inside the patient surrounded by the abdominal or thoracic walls.[3]

The da Vinci robotic system has been found to be extremely useful to approach and intervene in narrow cavities such as pelvis and it is gradually becoming a common practice (Fig. 1). The advantages further include stable camera platform to eliminate hand-tremor from a camera holder; hand-like motions of the instruments permitting a variety of tasks not possible with traditional straight laparoscopic instruments to facilitate dissection; a three-dimensional virtual operative field, with improved spatial awareness as compared to standard two-dimensional imaging systems; an ergonomically comfortable position to sit at the remote

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1743-9191/$ – see front matter © 2009 Surgical Associates Ltd. Published by Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijsu.2009.08.008

telerobotic console, reducing the shoulder and back fatigue associated with prolonged laparoscopic operations.[4] Conversion and complication rates are low and short-term outcomes are comparable to that of conventional laparoscopic surgery.[5]

We reviewed the literature with the aim to assess the current role of robotics in pelvic surgery (colorectal surgery, urology and gynaecology) in terms of its utility and outcomes. Issues pertaining to safety, reliability of robotic systems, training in robotic surgery and the future developments are also discussed.

2. Methods

We searched MEDLINE, EMBASE and the Cochrane databases from 1980 to 2009 for systematic reviews of randomised controlled trials, prospective observational studies, retrospective studies and case reports assessing robotic surgery. The search strings were defined by a combination of keywords including 'robotics' or 'robot' or 'robot-assisted' or 'da Vinci'. Additional search was performed for each of gynaecology, colorectal surgery, urology and pelvic surgery. The search was limited to articles in English language and relevant studies were evaluated including the reference lists.

3. Role in colorectal surgery

The first series of robotically assisted laparoscopic colectomy were published in March 2001.[6] Since then robotic assistance has been employed in hemicolectomies, sigmoid colectomies, proctopexies, low anterior resections and abdominoperineal resections (Table 1).[7–9]

Robot assisted anterior and abdominoperineal resections have been reported by various authors. D'Annibale et al. reported a comparison of 53 robotic and 53 laparoscopic procedures performed for colorectal diseases.[7] Although pelvic surgeries were not compared alone, 10 anterior resections and 1 abdominoperineal resection were performed in the robotic group and 15 anterior resections were performed in the laparoscopic group. No differences were seen in complication rates, estimated blood loss and lymph node harvest rates. Median length of hospital stay was 2.5 days in the robotic surgery group, vs. 3 days in the laparoscopic cohort. There was no significant difference in actual operating time (robotic group, 240 ± 61 min; laparoscopic group, 222 ± 77 min), but system and patient setup time (robotic group, 24 ± 12 min; laparoscopic group, 18 ± 7 min; $p = 0.002$), were relatively longer in the robotic group.[7]

Spinoglio et al. compared 50 robotic to 161 laparoscopic colorectal resections.[10] Similar to D'Annibale et el, pelvic surgeries were not compared separately, but there were 19 anterior resections and 1 abdominoperineal resection in the robotic group and 26 anterior resections and 7 abdominoperineal resections in the laparoscopic groups. There was a significant longer operative time in the robotic group (383.8 vs. 266.3 min, $p < 0.001$), but there were no differences in short-term outcomes such as restitution of gut function and length of hospital stay.

Pigazzi's group in California, reported by Hellan et al. and Anderson et al.,[11,12] performed 39 consecutive robotic assisted laparoscopic rectal resections with total mesorectal excision (TME) for primary rectal cancer. The study included the results of 22 low anterior, 11 intersphincteric and 6 abdominoperineal resections. The median operative time was 285 minutes (range 180–540 min) and a median robotic TME time of 60 minutes (range 35–135 mins). One patient required conversion to open surgery (conversion rate 2.6%). Ninety-five per cent of patients had a colo-anal anastomosis within 5 cm of the anal verge. Six patients had major postoperative complications (15%), including four anastomotic leaks, all requiring reoperation (12% leak rate), one delayed fistula and one patient with a neurogenic bladder and wound dehiscence. The median length of stay was 4 days. Total mesorectal excision with autonomic nerve preservation was achieved in all of the patients, and all circumferential and distal resection margins were negative. One patient died four months after surgery due to unrelated causes. There were no peri-operative (30-day) or cancer-related deaths.[11,12]

The largest series of robotic-assisted low anterior resections has been described by Baik et al.[13–15] In this prospective comparative non-randomised study consecutive rectal cancer patients were treated by laparoscopic low anterior resection (L-LAR) ($n = 57$) or robotic low anterior resection (R-LAR) ($n = 56$). There was no significant difference between mean operating time (L-LAR 191.1 ± 65.3 vs. R-LAR 190.1 ± 45.0 min). Patients who had L-LAR had significantly higher mean length of hospital stay (7.6 ± 3.0 vs. 5.7 ± 1.1 days, $p = 0.001$), open conversions (6 vs. 0 patients, $p = 0.013$) and serious complications (11 vs. 3 patients, $p = 0.025$). Serious complications included anastomotic leakage with 4 (7%) leaks in the laparoscopic group compared to 1 (2%) leak in the robotic group. TME was significantly better in the R-LAR group in comparison to the L-LAR group (52 complete, 4 nearly complete vs. 43 complete, 12 nearly complete, 2 incomplete, $p = 0.033$). However there was no difference in circumferential resection margin involvement (L-LAR 5 vs. R-LAR 3 involved).

The studies by Pigazzi et al. and Baik et al. demonstrate that robotic assisted rectal resections with TME can be performed safely and effectively using robotic assistance with lower serious complication rates than laparoscopic surgery. The reported leak rates of 2–12% is comparable to the 6–16% rate reported in open series and 13–19% in laparoscopic series.[16,17] The low conversion rate and reduced length of hospital stay in robotic surgery has important implications for clinical outcome.

4. Role in urological surgery

The fastest growing application of robotic pelvic surgery is in urological procedures such as prostatectomy and cystectomy.[18–20]

4.1. Robot-assisted radical prostatectomy for prostate cancer

Presently, radical prostatectomy (RP) is the most commonly performed robot assisted laparoscopic procedure (Table 2). Robotic RP (RRP) has traditionally been regarded as time consuming relative to open surgery. However, with increasing experience and

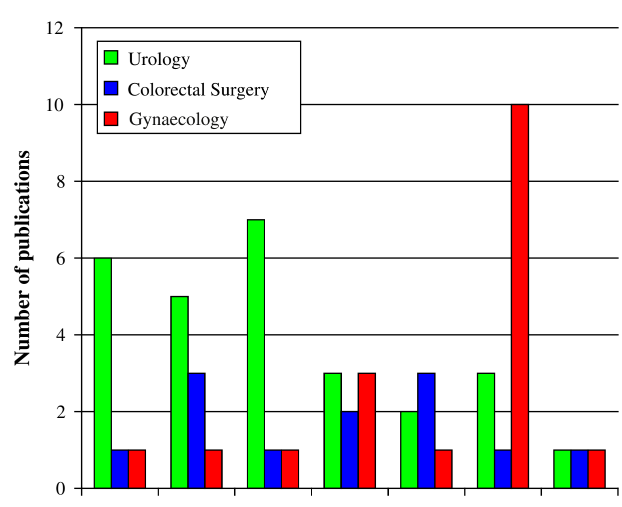

Fig. 1. Pelvic Robotic surgery in historical perspective.

Table 1
Published series for robotic-assisted colorectal resections.

Author	Institution	Year	n	Indications	System	Robot-assisted (RALC) or Total Robotic (TRLC)	Operative time min mean +/− SD or median (range)	Conversion %	Mortality %	Complications	LOS days mean +/− SD or median (range)
Giulianotti[60]	Misericordia Hospital, Grosseto, Italy	2003	16	Colon cancer n = 6 Rectal cancer n = 6 Anal melanoma n = 2 Caecal Lipoma n = 2	da Vinci	RALC	211 (90–360)	0	0	0	NR
Hanly[61]	Johns Hopkins University, Maryland, USA	2004	35	Diverticular disease and benign polyps	da Vinci	RALC	177	14	NR	NR	NR
Anvari[62]	McMaster University, Ontario, Canada	2004	10	Colon cancer n = 4 Rectal cancer n = 2 Benign n = 4	Zeus	RALC	155 ± 14	0	0	0	5.3 ± 0.95
D'Annibale[7]	Camposampiero, Padova, Italy	2004	53	Colon cancer n = 14 Rectal cancer n = 8 Benign disease n = 31	da Vinci	TRLC	240 ± 61	9	0	2 surgical – needed reoperation 2 general	10 ± 4
Braumann[6]	Humboldt University, Berlin, Germany	2005	5	Colon cancer n = 2 Rectal cancer n = 1 Diverticulosis n = 2	da Vinci	RALC	201 (80–300)	40	0	1 enterovesical fistula	13.6 ± 4.7
DeNoto[8]	North Shore University Hospital, New York, USA	2006	11	Sigmoid cancer and Sigmoid diverticulosis	da Vinci	TRLC	197 (145–345)	9	0	0	3.4 ± 0.5
Ballantyne[9]	Hackensack University, New Jersey, USA	2006	16	All benign disease	da Vinci	RALC	249 (180–330)	6	0	1 reoperation for bleeding 2 prolonged ileus	4.5 (2–10)
Rawlings (Right colectomies)[5]	University of Illinois, Illinois, USA	2007	Robotic 17 Laparoscopic 15	Polyps n = 20 (6/14) Cancer n = 8 (2/6) Diverticulitis n = 2 (0/2) Carcinoid n = 1 (1/0) Crohn's disease n = 1 (0/1)	da Vinci	TRALC vs. laparoscopic	Robotic 218.9 ± 44.6 Laparoscopic 169.2 ± 37.5	Robotic 0 Laparoscopic 13.3	0	Anastamotic leak, postoperative bleed, ileus	Robotic 5.2 ± 5.8 Laparoscopic 5.5 ± 3.4
'Rawlings (Sigmoid colectomies)[5]	University of Illinois, Illinois, USA	2007	Robotic 13 Laparoscopic 12	Diverticulitis n = 18 (8/10) Cancer n = 5 (3/2) Polyp n = 2 (2/0)	da Vinci	TRALC vs. laparoscopic	Robotic 225.2 ± 37.1 Laparoscopic 199.4 ± 44.5	Robotic 15.4 Laparoscopic 0	0	Caecal injury, tranverse colon injury, anasomotic leaks, wound infection	Robotic 6.0 ± 7.3 Laparoscopic 6.6 ± 8.3
Pigazzi[11,12]	City of Hope National Medical Center, California, USA	2007	39	All rectal cancer	da Vinci	RALC	285 (180–540)	12.1	0	Intra-operative bleeding, anastomotic leaks, reoperation, wound infection, urinary disorder, ileus	4 (2–22)
Spinoglio[10]	SS Antonio e Biagio, Alessandria, Italy	2008	Robotic 50 Laparoscopic 161	Cancer n = 172 (44/128) Benign n = 39 (6/33)	da Vinci	RALC vs. laparoscopic	Robotic: 383.8 Laparoscopic: 266.3	Robotic 4 Laparoscopic 4	0	Incisional hernia, lung atelectasia, wound infection, arm phlebitis, brain stroke, anastomotic leaks	Robotic 7.74 Laparoscopic 8.31
Baik[15]	Yonsei University College of Medicine, Seoul, Korea	2009	Robotic 56 Laparoscopic 57	All rectal cancer	da Vinci	RALC vs. laparoscopic	Robotic 190.1 ± 45.0 Laparoscopic 191.1 ± 65.3	Robotic 0 Laparoscopic 10.5	0	Intraluminal bleeding, anastomotic leak, ileus	Robotic 5.7 ± 1.1 Laparoscopic 7.6 ± 3.0

Table 2
Published series for robotic prostatectomy.

Author	Year	n	Operative time min mean +/− SD or median (range)	Mean estimated blood loss (ml)	Overall tumour rate (%) (pT2/pT3)	Complications (%)	Positive Surgical Margin rate (%)
Ahlering[63]	2003	45	209 (150–600)	145 (25–350)	60/35	13.3	35.5
Bentas[64]	2003	40	500 (246–780)	570 (100–2500)	62.5/37.5	32.5	30
Tewari[65]	2003	200	160 (71–315)	153 (25–750)	87/13	3.5	6
Wolfram[66]	2003	81	250 (150–390)	300 (100–1500)	68.5/31.5	–	22
Ahlering[67]	2004	200	–	108 (25–400)	72/26	6.7	20.4
Cathelineau[68]	2004	105	180 (120–290)	500 (150–2000)	71/29	–	22
Ahlering[69]	2005	109	70	92 (25–250)	–	8	13
Ahlering[71]	2005	100	247 (160–645)	120 (25–400)	75/25	9	25
Chien[72]	2005	56	356 (240–480)	356 (25–1200)	82/18	9	10.7
Costello[73]	2005	122	–	–	80/20	19	16.3
Joseph[74]	2005	50	202 +/− 38	206 +/− 63	88/12	8	12
Menon[75]	2005	76	115	102.3	95	–	3
Patel[76]	2005	200	141.2	75.1	78/19	1	10.5
Hu[77]	2006	322	186 (114–528)	250 (50–1600)	–	14.6	–
Menon[78]	2006	1142	154 (71–387)	142 (10–750)	77.7/22	2.3	13
Patel[79]	2006	500	130 (51–330)	50 (10–300)	78/20	–	9.4
Badani[80]	2007	2766	154 (71–387)	142 (10–1350)	77.7/22	14.9	12.3
Tewari[81]	2008	215	150 (120–240)	150	–	–	6.5
Tewari[82]	2008	700	–	–	83.5/14.1	–	5.2
Rocco[83]	2009	120	215 (165–450)	200 (50–2000)	73/24	–	22

refinements, the operating times are becoming comparable or even shorter. The mean blood loss after robotic surgery (152 mL) is significantly less than open (697 mL) and laparoscopic (406 mL) prostatectomy.[21] As a consequence, transfusion rate has been shown to be much lower than laparoscopic and open approaches. The mean catheter time for robotic procedure is similar to open and laparoscopic surgery.[21]

Most of the robotic prostate procedures are carried out for cancers. Cancer control remains the principal desirable outcome for any procedure with intent to cure. Berryhill et al.[21] used positive margin rate (PSM) to imply that the entire tumour was not excised. The mean PSM for robotic RPs was 12.5%, compared with 19.6% and 23.5% for laparoscopic RPs (LRP) and open RPs, respectively. The open and laparoscopic series included greater numbers of pT3 lesions, which could have an impact on negative margin rates. The overall complication rate for RRPs has been shown to be 6.6%, compared with 15.6% and 10.3% for laparoscopic RPs and open RPs, respectively. However, the gold standard randomised controlled trial is needed to further evaluate this.

Postoperative urinary continence is another critical outcome comparison to be considered. Robotic assisted radical prostatectomy outcomes for urinary continence range from 73% to 91% at 3 months, 98% at 12 months and 100% beyond 18 months. In contrast, laparoscopic assisted prostatectomy results are 51–94% at 3 months and 60–98% at 12 months. Long-term results for LRP are not available. For open prostatectomies, urinary continence results are 54%–70.9%, 60.5–92.1% and 58%–98.5% respectively at 3 months, 12 months and beyond 18 months follow-up.[21–23]

Table 3
Published series for robotic cystectomy.

Author	Year	n	Operative time min mean +/− SD or median (range)	Mean estimated blood loss (ml)	Urinary diversion	Surgical Margin
Beecken[84]	2003	1	Total 510	200	Extracorporeal	Negative
Menon[26]	2003	14	Cystectomy 140 Ileal conduit 120 Neobladde 168	150	Extracorporeal	Negative
Menon[27]	2004	3	Cystectomy 160 Ileal conduit 130 Neobladder 180	166	Extracorporeal	Negative
Balaji[25]	2004	3	Total 691	250	Intracorporeal	Negative
Hemal[85]	2004	23	Cystectomy 140 Urinary diversion 150	200	Extracorporeal	Negative
Pruthi[86]	2007		Total 366	313	Extracorporeal	Negative
Murphy[87]	2008	23	397 +/− 83.8	278 +/−229	Ileal conduit 19 Studer pouch reconstruction 4	Negative
Wang[70]	2008	54	Open 300 Robotic 390	Open 750 Robotic 400	Open: Ileal conduit 11 Indiana pouch 5 Orthotopic neobladder 5 Robotic: Ileal conduit 17 Indiana pouch 3 Orthotopic neobladder 12	Positive margins: 14% in open and 6% in robotic
Lee[88]	2009	6	–	296 (range 125–500)	Ileal conduit 5 Neobladder 1	Negative

Table 4
Published series for robotic procedures in gynaecology.

Author	Year	n	Study Type	Procedure	Estimated blood loss (ml) mean +/− SD or median (range)	Operative time (min) mean +/− SD or median (range)	Organ/ mass weight (gm)	Indications for surgery	Complications
Degueldre[36]	2000	8	Series	Tubal reanastomosis	–	140	–	–	–
Cadiere[89]	2001	28	Series	Tubal reanastomosis	–	125 (108–244)	–	–	None
Diaz-Arrastia[28]	2002	11	Series	Hysterectomy	300 (50–1500)	270–600	–	Recurrent cervical intraepithelial neoplasia-3, pelvic mass, postmenopausal bleeding, endometrial carcinoma, ovarian carcinoma	Conversion to laparotomy n = 1
Molpus[35]	2003	1	Series	Ovarian transposition	–	Adhesiolysis 108, Mobilization of the infundibulopelvic ligaments and suturing the ovaries into place 42	–	Stage I-B1 cervical squamous cell carcinoma (previous radical cystectomy)	–
Advincula[34]	2004	35	Series	Myomectomy	169 ± 198.7	230.8 +/−83	223.2–244.1	Intramural and subserous leiomyoma	Converted to laparotomy n = 2, difficulty in enucleation due to lack of tactile feedback n = 1, cardiogenic shock n = 1
Beste[90]	2005	11	Series	Hysterectomy	25–350	148–277	49–227	Menorrhagia, dysmenorrhea, pelvic pain, uterine fibroids	Conversion to laparotomy n = 1, Cystotomy n = 1
Fiorentino[29]	2006	20	Series	Hysterectomy	81	200	98	Menorrhagia, pelvic pain	Conversion to laparotomy n = 2, Vaginal cuff bleeding n = 1
Reynolds[30]	2006	16	Series	Hysterectomy	72.5 (50–300)	242 (170–432)	131.5 (30–327)	Abnormal uterine bleeding, chronic pelvic pain, uterine fibroids, adenomyosis, dysmenorrhea, pelvic mass.	Pneumonia n = 1, Bowel and bladder injury n = 1, Vaginal cuff hematoma n = 1, Wound cellulitis n = 1
Sert[91]	2006	15	Comparative (Robotic and Laparoscopic)	Radical Hysterectomy	71(median)	241(median)	–	Early-stage cervical carcinoma	
Advincula[92]	2007	58	Retrospective case matched analysis	Myomectomy	Robotic myomectomy (RM): 195.7 ± 228.6 Open myomectomy (OM): 364.7 ± 473.3	RM: 231.4 ± 85.1 OM: 154.4 ± 43.1	RM: 227.86 ± 247.54 223.76 ± 228.28	Symptomatic leiomyoma	–
Kim[93]	2008	10	Case series	Radical hysterectomy	355 (mean)	207 (mean)	–	Early stage carcinoma	No conversions
Fanning[32]	2008	20		Radical hysterectomy	300 (median)	310 (median)	–	Early stage carcinoma	–
Seamon[94]	2008	105	Series	Hysterectomy and pelvic–aortic lymphadenectomy	99 ± 83	242 ± 50	–	Stage I or occult Stage II endometrial carcinoma	Conversion rate 13%
Ko[95]	2008	16 Robotic vs. 32 Open	Comparative	Radical hysterectomy	82 vs. 666	290 vs. 239	–	Stage 1A2 or IBI endometrial cancer	No conversions

(continued on next page)

Table 4 (*continued*)

Author	Year	n	Study Type	Procedure	Estimated blood loss (ml) mean +/− SD or median (range)	Operative time (min) mean +/− SD or median (range)	Organ/ mass weight (gm)	Indications for surgery	Complications
Boggess[96]	2008	Open (138) vs. Lap (108) vs. Robotic (103)	Comparative	Total hysterectomy	TAH: 266 ± 184 TLH: 145.5 ± 105.6 TRH: 74.5 ± 101.2	TAH: 146.5 TLH: 213 TRH: 191	–	Stage IA to IVA/IVB endometrial cancer	Conversion rate: 2.9%
Boggess[97]	2008	Robotic (51) vs. open (49)	Case control	Type III radical hysterectomy	RAH: 96.5 ± 85.5 ORH: 416.8 ± 188	RAH: 211 ± 45.5 ORH: 247.8 ± 49	–	Stage IA2 to IB2 endometrial cancer	–
Bell[45]	2008	Robotic (40) vs. Open (40) vs. Lap (30)	Comparative	Radical hysterectomy	RH:166 OH: 316 LH: 253	RH: 184 OH: 108.6 LH: 171	RH: 136 OH: 155.6 LH: 138.5	–	–
Nezhat[98]	2008	Robotic (13) vs. Lap (30)	Comparative	Radical hysterectomy and pelvic lymphadenectomy	RRH: 157 LRH: 200	RRH: 323 LRH: 318	–	Cervical carcinoma	–
Veljovich[99]	2008	118	Series, Non-comparative	Hysterectomy ± lymphadencectomy, staging lymphadenectomy	71.3	213	104.8	Cervical cancer and endometrial cancer	Conversion to laparotomy n = 2
Magrina[100]	2008	Robotic (27) vs. Lap (31) vs. Open (35)	Comparative	Radical hysterectomy	RRH: 133 ± 108.5 LRH: 208.4 ± 105.4 ORH: 443.6 ±z 253	RRH: 189.6 ± 43.5 LRH: 220.4 ± 37.5 ORH: 166.8 ± 33.2	RRH: 122.4 LH: 122.8 ORH: 274.6	Cervical cancer and endometrial cancer	No conversions
Lowe[31]	2009	42	Multicentre, Non-comparative	Robotic-assisted type II ($n = 10$) and type III ($n = 32$) radical hysterectomy	50 (median)	215 (median)	–	Stage IA2 (n = 7), Stage I-B1 (n = 27), Stage IB2 (n = 6)	Conversion rate 2.4%

TAH: Total abdominal hysterectomy; TLH: Total laparoscopic hysterectomy; TRH: Total robotic hysterectomy; RAH: Robotic assisted hysterectomy; ORH: Open radical hysterectomy; RRH: Robotic radical hysterectomy; LRH: laparoscopic radical hysterectomy; ORH: Open radical hysterectomy.

Along with continence, sexual potency is a key outcome in determining quality of life after prostatectomy. With RRP, depending upon whether patients had unilateral or bilateral nerve sparing surgery, potency at 12 months has been reported to be 14.3–61% and 24.4–97% respectively. With LRP, 35–64% and 43–78.9% patients reported to have regained potency at 12 months with unilateral and bilateral nerve sparing surgery, respectively. Similar procedures with open prostatectomy show 16.7–53% and 36.7–86% results.[21] The interpretation of these results though difficult, shows an inclination towards RRP in producing more consistent results. A large scale randomised study is needed to establish clear benefits of one mode over the other.[21]

4.2. Robot-assisted radical cystectomy and urinary diversion

Robotic surgery is being utilized in radical cystoprostatectomy for male patients with bladder cancer and both standard and uterus sparing radical cystectomy in female patients (Table 3). Robotic radical cystectomy (RRC) is typically offered to patients with organ-confined bladder cancer as determined by preoperative clinical, pathological and radiographic findings. Presence of extensive lymphadenopathy, locally advanced disease, uncorrected coagulopathy, and obesity are relative contraindications for RRC.[24] Majority of surgeons use extracorporeal approach for reconstruction. However, a few who opt for purely robotic approach find the intracorporeal suturing of the ureteroileal anastomosis, neobladder anastomosis, and urethro-neobladder anastomosis easier. In a reported series of three patients the operative time for intracorporeal construction of ileal conduit was more than 10 hours.[25] However, Menon et al. clearly showed that operating time could be reduced with extracorporeal reconstruction of the urinary diversion.[26,27] Long-term functional and oncological outcomes of RRC in a larger series of patients remain awaited. To date nearly 300 cases have been performed worldwide.

5. Role in gynaecological surgery

The approaches by which gynaecological procedures are performed have also evolved. This is evident in transformation of hysterectomy, myomectomy, tubal reanastomosis and ovarian transposition from open trans-abdominal and vaginal approaches to laparoscopic techniques and then the robotic approach (Table 4).

Several authors have evaluated robot-assisted gynaecological procedures. Diaz-Arrastia et al.,[28] were the first to report a series of robotic assisted hysterectomy in 16 patients.[28] The operative time ranged from 270 to 600 min and the average blood loss was 300 ml.

The range of average hospital stay was 1–3 days. In this series, the posterior culdotomy and ligation of the cardinal and uterosacral ligament complexes were performed vaginally to complete the hysterectomy. Subsequently, others reported similar outcomes which were comparable to conventional laparoscopic hysterectomy.[29] Reynolds et al. reported the first series of 16 consecutive patients who underwent either type IVE robot-assisted laparoscopic hysterectomy (American Association of Gynaecologic Laparoscopists' classification) or Laparoscopic Supracervical Hysterectomy III hysterectomy (i.e. totally laparoscopic supracervical procedure with removal of the uterine corpus, including division of the uterine arteries). The mean uterine weight was 131.5 g (range 30–327 g). Median operating time was 242 minutes (range 170–432) with an average estimated blood loss of 96 ml (range 50–300 ml). One patient had delayed thermal bowel injury, 2 developed infections, and 1 had a vaginal cuff hematoma. The median length of hospital stay was 1.5 days.[30] From the results of above mentioned studies it can be established that the short-term outcomes of the robotic assisted procedures are comparable to laparoscopic and open procedures.

Lowe et al. in 2009, reported results of the largest multi-institutional study using da Vinci robot in gynaecologic oncology.[31] A total of 42 patients (median age of 41 and a median BMI of 25.1) who were included in the study who underwent a robotic-assisted type II ($n = 10$) or type III ($n = 32$) radical hysterectomy for early stage cervical cancer. The authors reported various outcome variables such as median operative time (215 min), median estimated blood (50 ml), median lymph node count ($n = 25$) and the median hospital stay (1 day). Positive lymph nodes were detected in 12% of the patients. Intra-operative complications (4.8%) included one conversion to laparotomy and one ureteral injury. Postoperative complications included a DVT (2.4%), infection (7.2%), and bladder/urinary tract complication (2.4%). The reported conversion rate to laparotomy was 2.4%.[31] Fanning et al. in their study (radical hysterectomy, $n = 20$) reported long term results. Ninety of their patients were disease free after 2 years.[32]

Surgical technique employing robot-assistance allows the surgeons to overcome difficulties encountered during conventional laparoscopic hysterotomy, enucleation, repair, and extraction.[33] Advincula et al.,[34] in a series involving 35 patients, have further demonstrated comparable operating time, blood loss and hospital stay to laparoscopic surgery.[34] Other applications of robotic surgery in gynaecology include tubal reanastomosis, cancer staging and abdominal sacrocolpopexy.[30,35–37]

6. Training of surgeons in robotic surgery

Technological advances in the field of surgery are pacing at a rate much faster than that in surgical training. The reduction in training hours poses an additional challenge to training the future surgeon in newer technologies including robotics. Therefore the need to speed up the learning curve of trainees is more imminent than ever. In Europe there are several centres where trainees can learn robotic surgical techniques on live animal models. Although, these models provide a simulation experience comparable to real patients, resource limitation and ethical concerns can be a deterrent in wider application of these training methods. In view of these issues, there is an urgent need to research into virtual reality and synthetic models for training and accreditation. Fortunately, da Vinci robotic virtual reality simulators are available which can be used not only to teach robotic skills but can also be used to differentiate between expert and novice surgeons.[38] Some centres have demonstrated that robotic surgery training can be implemented in structured training programmes.[39] However, trainers face new challenges of teaching trainees to assist and perform surgery when not physically standing at the operating room table.[40]

7. Safety and reliability

Robotic surgery has emerged as a feasible option for routine surgical procedures in the past few years. There have been studies looking into reported malfunctions and associated patient harm. The review of MAUDE (Medical Device Reports) database of the FDA (Food and Drug Administration) from 2000 to August 2007 reported an overall failure rate of 0.38% of which mere 4.8% were associated with patient injury.[41,42] No intra-operative device failures were observed in a study by Zorn et al, involving 725 robotic prostatectomies in a single centre.[42] Moreover, the da Vinci robot has proven its safety and efficacy in a randomised clinical trial involving 200 patients and has hence been approved by FDA.[3]

8. Cost of robotic surgery

The use of robotics in pelvic surgery is increasing but the cost (da Vinci S system costs approximately €1.5 million) remains a major limiting factor.[43] Eight hundred and sixty eight units were sold worldwide until early 2008, 647 in the United States, 148 in Europe and 72 in rest of the world (Intuitive Surgical).

The overall cost of robotic practice is variable for different procedures. The direct procedural cost has been reported to be less for the open (median $2322) than the robotic assisted prostatectomy (median $3352). However, the total hospital cost for a robotic procedure (median $9343) is less than the open (median $9724).[44] This may be due to the short hospital stay and relatively less stay related complications. For colorectal surgeries, Rowling et al, who compared costs of robotic assisted colonic resections with conventional laparoscopic resections, found that the total hospital expenditures for all types of resections were higher for robotic procedures as compared to laparoscopy.[5] In gynaecological surgery, staging laparotomy prior to hysterectomy costs around $12,943.60, whereas that for standard laparoscopy and robotic procedures cost $7569.80 and $8212.00 respectively. Total hospital cost for robotic surgery is less than the open surgery.[45]

Clearly in all major pelvic surgeries, despite initial cost of setting up a robot and higher operative expenditures, the total spending per patient is comparable to the laparoscopic procedures due to reduced hospital stay and fewer stay related complications. With time, as the technology is becoming cheaper; the costs will reduce rapidly.

9. Current limitations of robotic technology

The excursion arcs of the robotic arms and the length of the surgical instruments are potential limitations of the da Vinci system. Some difficulties are reported with the robotic instruments in reaching higher up to the splenic flexure and down into the pelvis. The robotic arms cannot self-adjust around the bed to allow the surgeon access to more than one quadrant of the abdominal cavity at one time. Hence to perform dissections in different areas may require repositioning of the surgical cast during various stages of the operation. Moving the da Vinci system is time consuming and difficult because the robotic devices are heavy and bulky. To address this issue, recently a new generation da Vinci S robot has been introduced with improved resolution screen enhancing user-interface. Also, it consists of a motorised patient cart and efficient mounts for faster patient docking. With the 4th arm integrated, deployment is rapid and smooth.[46] These improvements are likely to reduce the operative duration in future, but before implementation into the clinical practice evidence on clinical safety is required.

Other disadvantages are lack of tactile and tensile feedback, therefore the surgeon has to rely on visual cues to estimate the tension exerted on tissue. In order to avoid injuries, particular care must be taken with tissue handling.[47] Robot-assisted laparoscopic colectomy and other colorectal procedures require further evaluation as regards to the oncological and functional outcomes, before introduction to routine practice. Role of robotics is still limited in cases requiring multi-quadrant surgery.[48]

10. Future developments

The advent of robotics has clearly taken surgical technology to a new level. In conventional laparoscopy the visual experience is limited to 2-D but da Vinci system offers the surgeon a 3-D view. Although it improves the dexterity, limited tactile feedback is a major compromise. Currently a lot of research is underway to overcome this barrier. In 2006, Schostek et al. successfully incorporated a tactile sensor system in a laparoscopic grasper for surgical palpation in minimally invasive surgery. The tactile data is then presented visually to the surgeon. The system has been tested in the experimental settings.[49] Akinbiyi et al. have designed a similar system which is integrated into da Vinci system.[50] Fischer et al. have designed a system in which tactile data is fed as vibration onto surgeon's fingertips.[51]

To date, robots have been widely used and tested for laparoscopic surgery. With the emergence of Natural Orifice Translumination Endoscopic Surgery (NOTES) as a no scar surgical option, the role of robots has generated a renewed interest. On animal models Haber et al. performed pyeloplasties and nephrectomies using da Vinci robotic arms placed per-vaginally and reported a significantly enhanced experience of intracorporeal suturing.[52]

Research is also underway to develop freely mobile robots to reduce fulcrum effect, improve dexterity and visualisation inside the peritoneal cavity.[53] Rentschler et al. have designed an untethered robot which can be inserted through the mouth and then through a gastrostomy into the peritoneal cavity for remote controlled exploration.[54]

The experience with robotic assisted remote telesurgery has opened up exciting possibilities of surgeons operating in extreme environments such as isolated locations or on battlefield frontlines.[55] Anvari et al. recently reported the McMaster experience in telepresence surgery. Between 2003 and 2005, 22 remote telerobotic operations were performed between the teaching centre and a remote provincial hospital over 350 km away.[56,57] Time delays in telecommunication of 150–200 ms were experienced during most procedures, and the surgeons found that when the delay exceeded 250 ms, performing tasks telerobotically became slow and less accurate. More work is being carried out to improve this technology.

Recently, a prototype intra-abdominal mobile robot with the potential to enhance the safety of minimal access surgery has been developed. Under endoscopic control, a gastrotomy was created, and the miniature robot was deployed into the abdominal cavity under remote control. The robot is 12 mm in diameter and 75 mm in length. This prototype endoluminal mobile robot was connected to a power cable during the porcine surgery. A wireless *in vivo* mobile robot also has been developed. The gastrostomy incision was successfully closed endoscopically using two endoclips and one endoloop. The robot was then retracted back through the oesophagus.[54]

Robotic systems that are interfaced with computed tomography, magnetic resonance imaging scans and ultrasound information can create a virtual surgical environment. This virtual scenario enables simulated surgery to be performed based on a patient's individual imaging information, facilitating the preparation of operative strategies for challenging and complex cases.[58]

The surgical trauma may be reduced without compromising surgical access by using a family of robots working together inside the abdominal cavity after simple insertion through the oesophagus. Though these developments are still in experimental stages, they forecast a showcase for the surgery of tomorrow. Moreover, the introduction of robotic surgery into operating theatres also poses a challenge to the existing theatre design. Most of the theatres have been designed for the conventional surgical procedures. Over the passage of time very limited modifications have been made to accommodate the laparoscopic stacks. New theatre designs such as *Karl Storz OR1* have integrated the laparoscopic stacks into manoeuvrable ceiling mounted columns with high definition capabilities and surround screens. The controls for the camera and insufflators have also been modernized for quick and easy access. Audio and video recording capabilities are more sophisticated to promote retrospective learning, research and mentoring. In order to improve theatre ergonomics, the design of future operating theatres needs a considerable transformation.[59]

11. Conclusions

Robotic surgery appears to have a significantly potential role in pelvic surgery. Just as conventional laparoscopic surgery has proven to be a transitional technology, the current generation of surgical robots are likely to be replaced by more efficient machines. In the meantime suitably designed randomised clinical trials for appropriate procedures are prudent in order to obtain the outcome data necessary to convince the critics of robotic pelvic surgery. The required data include studies showing convenience of the surgeon, benefit to the patient and comparable or better long-term outcomes.

Conflict of interest
None declared.

Funding
None declared.

Ethical approval
None declared.

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